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The Dynamic Characteristics on the Wall Traveling of the HTS Bulk Superconducting Actuator

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Abstract

The electric device applications of a high temperature superconducting (HTS) bulk having stable levitation and suspension properties due to their strong flux pinning force have been proposed and developed. We have been investigating the three-dimensional (3-D) superconducting actuator using HTS bulk to develop the transportation device with non-contact and moves in free space. It is expected that our proposed 3-D superconducting actuator to be useful as a transporter used in clean room which manufactures the silicon wafer where dislikes mechanical contact and dust. Proposed the actuator consists of a field-cooled HTS bulk for mover and two-dimensional arranged multiple electromagnets as a stator. In our previous study, the dynamic characteristics on the floor traveling of the HTS bulk mover had been studied. Therefore in this study, a system for the wall traveling was proposed to use the limited space effectively. It is expected that the wall traveling system is very useful to apply the transporter used in the tunnels which flammable gas may be produced. In this paper, the optimal angle between electromagnets located at floor and wall for moving to the wall traveling from the floor traveling was investigated experimentally. The position displacement on the rotating of the HTS bulk during the wall traveling was measured. As a result, the bulk with initial gap of 2 mm could move to the wall traveling from the floor traveling. Also, the position displacement on the height direction during the rotating of the HTS bulk was 18 mm from the initial position because of its gravity ,but it was possible to rotate by changing the pattern NSNS of the trapped magnetic field in near the initial position.

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Keywords: trapped magnetic field; superconducting actuator; HTS bulk mover; wall traveling; levitation height of HTS bulk

1. Introduction

We have been investigating the 3-D HTS bulk superconducting actuator in order to use as a non-contact transportation device which moves freely in space [1-4]. The proposed 3-D superconducting actuator consists of an HTS bulk (mover), 2-D arranged electromagnets (stator) and controller including power supplies. In our previous works, the dynamic characteristics on the floor traveling of the HTS bulk mover were studied. Therefore in this study, a system for the wall traveling was proposed to use the limited space effectively. So, the conditions capable of moving to the wall traveling from the floor traveling were investigated experimentally. Also the rotating characteristics of the bulk during

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the wall traveling was measured in order to diversify the wall traveling with moving horizontally, vertically, and obliquely.

2. Concept of wall traveling

2.1. Electromagnet and HTS Bulk

We have been fabricating the 3-D HTS bulk superconducting actuator. The detailed specifications and study contents of it are shown in previous papers [1-4]. In the previous works, we had used the DC electromagnets, called "4-pole electromagnets", as shown in Fig. 1 (a). To improve the rotating characteristics of HTS bulk, we used the DC electromagnets, called "8-pole electromagnets", as shown in Fig. 1 (b). Both of DC electromagnets are composed of iron cores and wound with Cu wire. The disk-shaped GdBCO HTS bulk with 60 mm in diameter, 15 mm in thickness and 270 g in weight was used as a mover. This HTS bulk was reinforced by 2 mm thickness stainless steel and impregnated by epoxy to prevent a mechanical stress.

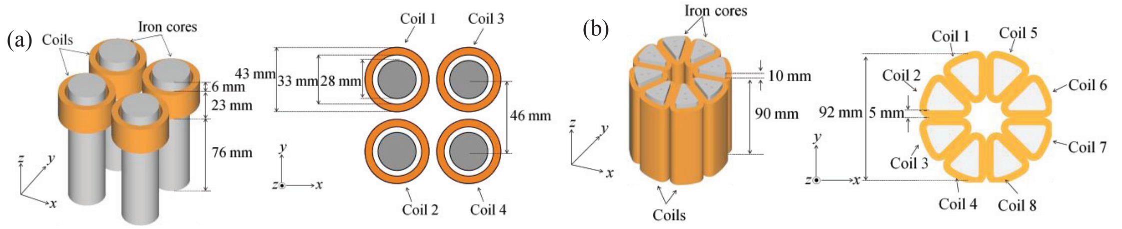

Fig. 1. Schematic illustrations of the two types electromagnets (a) 4-pole electromagnets and (b) 8-pole electromagnets.

2.2. Wall traveling

Fig.2 shows the schematic illustrations drawing of experimental device for moving to the wall traveling from the floor traveling. The HTS bulk mover cannot move to the electromagnets located at wall from the electromagnets located at floor. So the bulk needs to move to the electromagnets inclined against the floor direction from the electromagnets located at the floor and move to electromagnets located at the wall from the electromagnets inclined against the floor direction as shown in Fig. 2. Fig. 3 shows the schematic illustration drawing of 4-pole and 8-pole electromagnets located at the wall. The arranged electromagnets enable the bulk to move horizontally, vertically, and obliquely by rotating on the 8-pole electromagnets during the wall traveling.

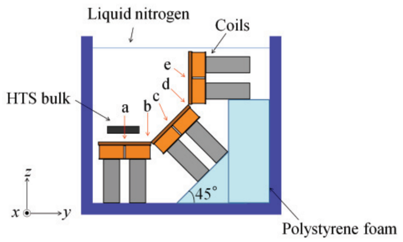

Fig. 2. Schematic cross-sectional drawing of an experimental device for moving to the wall traveling from the floor travelling.

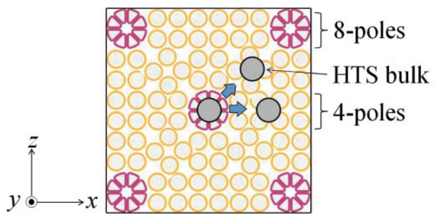

Fig. 3. Schematic cross-sectional drawing of 4-pole and 8-pole electromagnets located at the wall.

3. Experimental details

The HTS bulk mover was magnetized by the field cooling (FC) method. The bulk and electromagnets were placed in the foamed polystyrene container filled with liquid nitrogen. In FC method, the bulk was located on the center of 4-pole electromagnets or 8-pole electromagnets, DC current at 9A was transported, with the gap lengths between top surface of electromagnets and bulk (0 and 2 mm). Here, we call this gap "initial gap". The drive currents of 4-pole electromagnets were measured for moving to the wall traveling from the floor traveling. The axial components of the trapped magnetic fields were measured by the hall probe attached to an X-Y transporter. The levitation height was measured by the ruler. The levitation height was measured as a function of various drive currents from 4 A to 15 A. The rotating characteristics of the bulk were observed by digital camera and the video images (240 frames per second) were analyzed to investigate the bulk position during the wall traveling.

4. Results and Discussion

4.1. Moving to the wall traveling from the floor traveling

Table. 1 shows the drive current for moving to the wall traveling from the floor traveling with the HTS bulk mover of pattern NNSS magnetized by 4-pole electromagnets. Here, we call this pattern "pattern A". The bulk with the initial gap of 0 cannot move to point e from point c as shown in Fig. 2. The bulk contacted with the electromagnets so the levitation position of the bulk was not enough. Therefore, the bulk with the initial gap of 2 mm can levitate higher than the bulk with the initial gap of 0 and the bulk with the initial gap of 2 mm was suitable for moving to the wall traveling from the floor traveling.

Table 1. Drive current for moving to the wall traveling from the floor traveling (the HTS bulk was magnetized by pattern A).

Moving pass of the HTS bulk	Gap (*mm*)	Drive current (*A*)
a → b	0	10~12
	2	9~12
b → c	0	10~12
	2	9~12
c → d	0	-
	2	9~12
d → e	0	-
	2	9~12

4.2. The trapped magnetic field properties of HTS bulk and levitation height

Fig. 4 shows the trapped magnetic field maps at 1 mm above top surface of HTS bulk mover of pattern NNSS and NSNS magnetized by 4-pole electromagnets, and pattern NNNNSSSS and NNSSNNSS magnetized by 8-pole electromagnets. Here, we call this pattern NSNS "pattern B", this pattern NNNNSSSS "pattern C" and this pattern NNSSNNSS "pattern D". The maximum trapped magnetic field strength of 4-pole electromagnets was larger than 8-pole electromagnets as shown in Fig. 4. Fig. 5 shows the levitation height of the bulk magnetized by 4-pole electromagnets and 8-pole electromagnets when the bulk levitated on 8-pole electromagnets. The bulk with the initial gap of 2 mm levitated higher than that of 0 because the levitation height strongly depend on the strength of magnetic field. Also, the levitation height of the bulk of pattern B and pattern D was proportional to the drive current in levitation height of 2 mm or less, however it was not proportional to the drive current in levitation height of 2 mm or more because the levitation force became lower when the levitation height was higher.

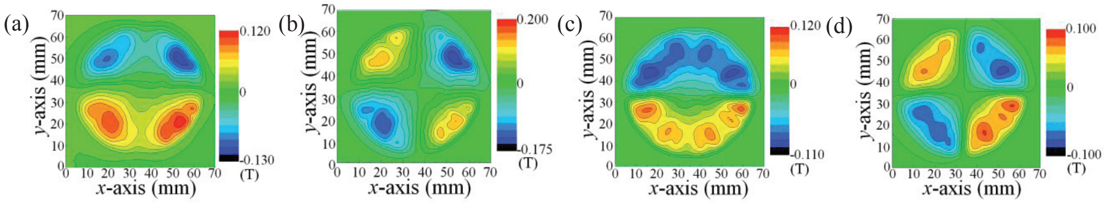

Fig. 4. Measured the trapped magnetic field contour maps (70×70 mm^2) at 1mm above the top surface of HTS bulk mover magnetized by (a) pattern A, (b) pattern B, (c) pattern C and (d) pattern D.

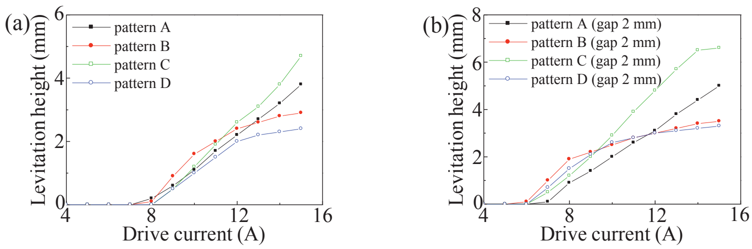

Fig. 5. Measured the levitation height of HTS bulk magnetized by pattern A, pattern B, pattern C and pattern D with (a) initial gap of 0 and (b) initial gap of 2 mm.

4.3. Rotating characteristics

Fig. 6 shows the position displacement of the HTS bulk mover with the initial gap of 0 at 45 ° rotating. Fig. 7 shows the position displacement of the bulk with the initial gap of 2 mm at 45 ° rotating. The bulk with initial gap of 2 mm of patterns A and C could not rotate because HTS bulk mover fell down. Also the bulk with initial gap 0 of pattern C could not rotate because of the same reason of initial gap of 2 mm. Therefore, the trapped magnetic field strength of the bulk of patterns A and C was lower than the bulk of patterns B and D. The trapped field gradient of the bulk contributes to the stable levitation and the field gradient between N pole and S pole is larger than the field gradient between N pole and N pole. The position displacement of the bulk of pattern A on height direction was 18 mm from the initial position, so there was the trapped magnetic field of N pole and N pole against height direction. From Fig. 7, the position displacement of the bulk of pattern D on height direction was larger than that of pattern B. The reason was that the stable levitation of the bulk of pattern B was better than that of pattern D because the trapped magnetic field strength of the bulk of pattern B was larger than pattern D. Also, the difference between low position and high position of the stable levitation of the bulk magnetized by 8-pole electromagnets was larger than the bulk magnetized by 4-pole electromagnets because the shape of trapped magnetic field of the bulk magnetized by 8-pole electromagnets was nearer to the shape of the generated magnetic field at rotation. Therefore, the rotating speed of the bulk magnetized by 8-pole electromagnets was faster than the bulk magnetized by 4-pole electromagnets when the bulk rotated from the low position of stable levitation to the high position of the stable levitation.

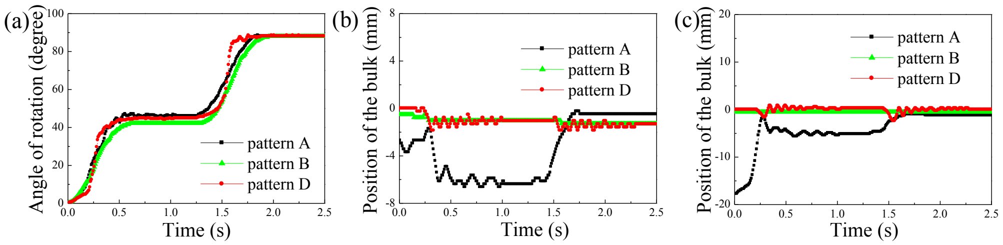

Fig. 6. Measured the position displacement of HTS bulk mover with the initial gap of 0 at 45° rotation
(a) angle of rotation, (b) *x*-axis direction and (c) *z*-axis direction.

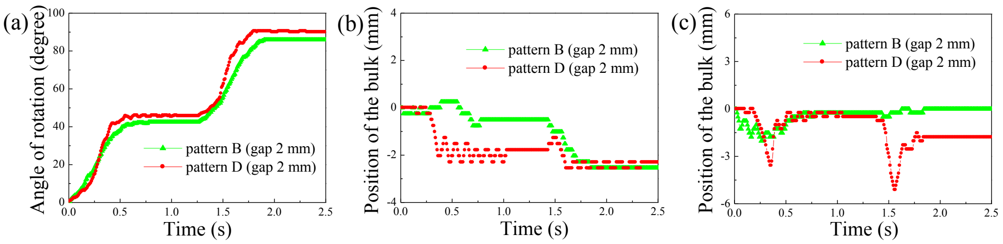

Fig. 7. Measured the position displacement of HTS bulk with the initial gap of 2 mm at 45° rotation
(a) angle of rotation, (b) *x*-axis direction and (c) *z*-axis direction.

5. Conclusion

It is expected that proposed the wall traveling system is very useful to apply the transporter used in the tunnels which flammable gas may be produced. Therefore, the dynamic characteristics on the wall traveling were investigated. From the experimental results, the HTS bulk mover needs to move to the electromagnets inclined against the floor direction from the electromagnets located at floor and move to the electromagnets located at wall from the electromagnets inclined against the floor direction. The bulk with initial gap of 2 mm could move to the wall traveling from the floor traveling because the bulk with the initial gap of 2 mm could levitate higher than the bulk with the initial gap of 0. Also it was confirmed that it was possible to rotate by changing the pattern of the trapped magnetic field.

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